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New High-Resolution Sunyaev-Zel'dovich Observations with GBT+MUSTANG

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Abstract. We present recent high angular resolution (9″) Sunyaev-Zel'dovich effect (SZE) observations with MUSTANG, a 90-GHz bolometric receiver on the Green Bank Telescope. MUSTANG has now imaged several massive clusters of galaxies in some of the highest-resolution SZE imaging to date, revealing complex pressure substructure within the hot intra-cluster gas in merging clusters. We focus on three merging, intermediate redshift clusters here: MACS J0744.8+3927, MACS J0717.5+3745, RX J1347.5-1145. In one of these merging clusters, MACS J0744.8+3927, the MUSTANG observation has revealed shocked gas that was previously undetected in X-ray observations. Our preliminary results for MACS J0717.5+3745 demonstrate the complementarity these observations provide when combined with X-ray observations of the thermal emission and radio observations of the non-thermal emission. And finally, by revisiting RX J1347.5-1145, we note an interesting correlation between its radio emission and the SZE data. While observations of the thermal SZE probe the line of sight integral of thermal electron pressure through a cluster, these redshift independent observations hold great potential for aiding the interpretation of non-thermal astrophysics in high-z clusters.

1. Introduction

The Sunyaev-Zel'dovich effect (SZE), due to inverse Compton scattering of photons from the Cosmic Microwave Background (CMB) off electrons in the intra-cluster medium (ICM) (Zel'dovich & Sunyaev 1969), has long been sought as a probe of cluster astrophysics and cosmology (e.g. Birkinshaw 1991; Carlstrom et al. 1996). SZE surveys like those with the Atacama Cosmology Telescope (Kosowsky 2003), the South Pole Telescope (Ruhl et al. 2004), and *Planck* (Rosset et al. 2010) are now discovering new clusters. With notable exceptions (e.g. Komatsu et al. 2001), these and other SZE instruments have resolutions $\sim$1–7′, and therefore do not typically probe clusters on scales $\lesssim$ 1 Mpc.

Recently, the **MU**ltiplexed **S**QUID/**T**ES **A**rray at **N**inety **G**Hz (MUSTANG), a receiver on the 100-m Green Bank Telescope (GBT), has observed the SZE from clusters at 9″ resolution (Mason et al. 2010; Korngut et al. 2010). At this resolution, the thermal SZE provides a probe of subcluster scales, complementary to X-ray studies. In these proceedings, we discuss these MUSTANG observations and share the preliminary results from a new observation taken in the 2010C trimester. We discuss the instrument in § 2, present recent results in § 3, and discuss future directions for MUSTANG in § 4.

2. GBT+MUSTANG

MUSTANG is a cryogenic, re-imaging focal plane camera with an 8×8 array of transition edge sensor (TES) bolometers cooled to ≈ 0.3 K. The MUSTANG receiver was built at UPenn and at 90 GHz is the highest frequency instrument on the GBT. Using capacitive mesh filters to define the bandpass, MUSTANG has $\approx$ 19 GHz bandwidth for continuum imaging. The array has a $0.63 f\lambda$ pixel spacing which yields a well-sampled 42″ instantaneous field of view with $\sim$ 9″ resolution. For more details, see Dicker et al. (2009) and the MUSTANG web site.[1]

3. Results

Due to common mode subtraction of the atmosphere, spatial scales larger than $\sim$1.5–2$\times$ the 42″ instantaneous field of view are severely attenuated from MUSTANG observations. The resulting high-pass filtered observations of the thermal SZE provide a measure of line of sight integrated pressure.[2] They are well-situated to complement other SZE instruments by measuring cluster substructure on 0.15–1′ scales, but do not recover the extended SZE flux used to determine scaling relations (e.g. Bonamente et al. 2008). The observations we present here illustrate MUSTANG's utility in revealing shock-heated and disturbed ICM.

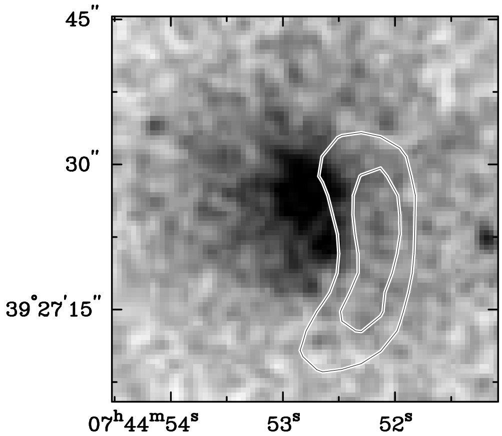

Fig. 1. MACS J0744.8+3927: *Chandra* X-ray image with MUSTANG SZE 4 and 5-σ contours overlaid. X-ray analysis guided by this SZE feature unveils a significant drop in X-ray surface brightness and a rise in temperature, indicating shock-heated gas with Mach number $\mathcal{M} = 1.2 \pm 0.2$.

3.1. MACS J0744.8+3927 ($z = 0.69$)

MACS J0744.8+3927 was discovered in the ROSAT All-Sky Survey (RASS) and is part of the **MA**ssive **C**luster **S**urvey (MACS Ebeling et al. 2001, 2007), a sample of some of the most massive clusters at $z > 0.3$. As reported in Korngut et al. (2010), MUSTANG observations of this cluster revealed a feature in the line of sight pressure, offset from X-ray surface brightness peak (see Fig. 1). In fact, the inside edge of the SZE feature aligns with an X-ray surface brightness discontinuity.

Using the MUSTANG observations as a guide, Korngut et al. (2010) analysed the available 90 ksec of *Chandra* data. We interpret the X-ray surface brightness peak as the intact core of the main cluster, and the MUSTANG selected feature as shock-heated gas. The gas to the west of both the MUSTANG selected feature and the second X-ray surface brightness

[1] http://www.gb.nrao.edu/mustang/

[2] Other manifestations of the SZE include: the kinematic SZE, proportional to the line of sight proper motion of the ICM, the polarized SZE, proportional to the transverse motion of the ICM, and the non-thermal SZE, proportional to relativistic electrons in the ICM. See e.g. Carlstrom et al. (2002).

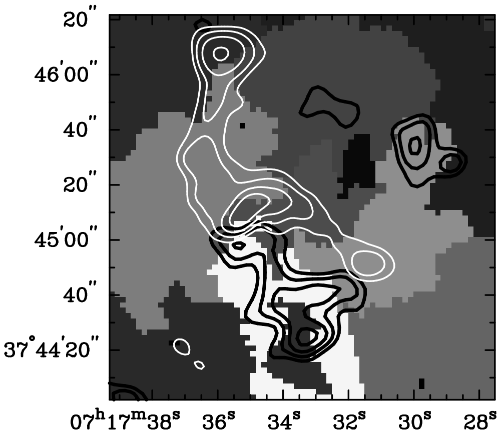

Fig. 2. MACS J0717.5+3745 preliminary data: Ma et al. (2009) temperature map with MUSTANG S/N (black) and GMRT 600 MHz (white) contours from van Weeren et al. (2009) overlaid. The peak SZE detection is cospatial with the hottest (~24 keV, in white) region identified in the temperature map, and is bordered by the radio relic to the north.

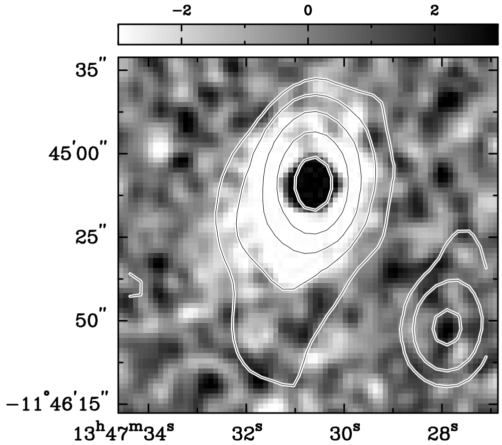

Fig. 3. RX J1347.5-1145: MUSTANG S/N map with VLA 1.4 GHz contours from Gitti et al. (2007) overlaid. The SZE decrement at >3-σ corresponds to the radio emission at found at >9-σ. Both are enhanced to the southeast, outside the cool core. The central point source in the MUSTANG map was detected at ~40-σ, and is fully saturated in this map.

discontinuity is likely the pre-shock medium. We derive a best fit Mach number $\mathcal{M} = 1.2 \pm 0.2$ (Korngut et al. 2010), implying this is a fairly weak shock, marginally consistent with being transonic.

3.2. MACS J0717.5+3745 ($z = 0.55$)

MACS J0717.5+3745, also found in MACS, exhibits many signposts of on-going merger activity. Optical observations show this cluster to have the largest known Einstein radius and a complicated mass distribution (Zitrin et al. 2010). Radio observations with the VLA and GMRT have revealed what is likely a relic (Bonafede et al. 2009; van Weeren et al. 2009) due to electrons re-accelerated to relativistic energies by a shock. X-ray observations reveal a complex ICM morphology and regions with temperatures as high as $\sim$ 24 keV (Ma et al. 2009), indicating a sharp pressure discontinuity to the south of the radio relic. The preliminary MUSTANG data help complete this picture: the peak in the MUSTANG maps agrees well with the position of the hot gas seen in the X-ray (see Fig. 2).

3.3. RX J1347.5-1145 ($z = 0.45$)

RX J1347.5-1145, another member of MACS, is the most X-ray luminous cluster known. While its X-ray emission is dominated by its relaxed cool core, there is substantial evidence pointing to a high impact parameter merger. High resolution SZE measurements with Nobeyama (Komatsu et al. 2001) indicated (at ~3-σ) the presence of a pressure enhancement to the southeast. The Nobeyama result was soon confirmed by X-ray observations (Allen et al. 2002). MUSTANG later improved upon the significance of the SZE result to many sigma in its first cluster observation (Mason et al. 2010). Interestingly, radio emission from RX J1347.5-1145, predominantly due to the mini-halo associated with the relaxed cool core, shows a similar southeast enhancement (Gitti et al. 2007). In Fig. 3, we show that the SZE decrement is co-spatial with the radio emission.

4. Conclusions & Future Work

MUSTANG has been pioneering in the study of cluster astrophysics and substruc-

ture through the SZE. The clusters targeted in MUSTANG observations to date, however, have been chosen in an ad hoc fashion. To address this, we are moving to image a cluster sample down to a uniform depth, confirming or rejecting the presence of cluster substructure that would affect SZE scaling relations at the level of a few percent.

We are also working to improve our analysis tools. Notably, we will soon be able to remove point source contamination from, and fit cluster models to, the time ordered data. This will provide a method by which to fit MUSTANG data jointly with X-ray data and that from other SZE instruments.

Most tantalizing of all, we have proposed a successor instrument to MUSTANG, MUSTANG2, which is designed to have a larger instantaneous field of view ($4.5'$) and $\gtrsim 30\times$ higher sensitivity than MUSTANG. Observations that currently take hours with MUSTANG could be performed in a matter of minutes, imaging the SZE at $\sim 9''$ resolution and recovering SZE flux out to $\sim 9'$ scales. This upgrade is crucial as the GBT is heavily subscribed, and MUSTANG's high-frequency observations demand the best observing conditions Green Bank, West Virginia, has to offer. This upgrade will also ensure GBT+MUSTANG2 will remain competitive as ALMA comes online, as MUSTANG2 will provide an order magnitude better mapping speed for continuum emission at 90 GHz than the 50-element ALMA.

References

Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 335, 256
Birkinshaw, M. 1991, in Physical Cosmology, 177
Bonafede, A., Feretti, L., Giovannini, G., et al. 2009, A&A, 503, 707
Bonamente, M., Joy, M., LaRoque, S. J., et al. 2008, ApJ, 675, 106
Carlstrom, J. E., Holder, G. P., & Reese, E. D. 2002, ARA&A, 40, 643
Carlstrom, J. E., Joy, M., & Grego, L. 1996, ApJ, 456, L75
Dicker, S. R., Mason, B. S., Korngut, P. M., et al. 2009, ApJ, 705, 226
Ebeling, H., Barrett, E., Donovan, D., et al. 2007, ApJ, 661, L33
Ebeling, H., Edge, A. C., & Henry, J. P. 2001, ApJ, 553, 668
Gitti, M., Ferrari, C., Domainko, W., Feretti, L., & Schindler, S. 2007, A&A, 470, L25
Komatsu, E., Matsuo, H., Kitayama, T., et al. 2001, PASJ, 53, 57
Korngut, P. M., Dicker, S. R., Reese, E. D., et al. 2010, ArXiv e-prints
Kosowsky, A. 2003, New Astronomy Review, 47, 939
Ma, C., Ebeling, H., & Barrett, E. 2009, ApJ, 693, L56
Mason, B. S., Dicker, S. R., Korngut, P. M., et al. 2010, ApJ, 716, 739
Rosset, C., Tristram, M., Ponthieu, N., et al. 2010, A&A, 520, A13+
Ruhl, J., Ade, P. A. R., Carlstrom, J. E., et al. 2004, 5498, 11
van Weeren, R. J., Röttgering, H. J. A., Brüggen, M., & Cohen, A. 2009, A&A, 505, 991
Zel'dovich, Y. B. & Sunyaev, R. A. 1969, Ap&SS, 4, 301
Zitrin, A., Broadhurst, T., Barkana, R., Rephaeli, Y., & Benitez, N. 2010, ArXiv e-prints

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